Impact of Pump Quality on the Performances of Fiber Optical Parametric Amplifiers

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***Abstract*— The principle of operation of fibre optical parametric amplifiers is revisited with a special attention to the pump wave characteristics ranging from the monochromatic coherent case to the incoherent one.**

I. INTRODUCTION

Initially studied in the 80's [1], [2], then largely abandoned as a research field due to technological limitations, it is until recently that major breakthroughs, including the development of highly nonlinear fibres and efficient Brillouin suppression techniques, have brought parametric amplification back on the research scene and positioned it as a leading technology for future all-optical ultrafast signal processing [3]–[5]. Despite the vast number of papers published however, it is remarkable that some of the fundamental processes behind the parametric amplification of light in optical fibres are still poorly understood. In particular, the impact of pump incoherence, or, more precisely, of the field amplitude and phase random fluctuations, on the performances of fibre parametric amplifiers has not been fully considered yet. A typical example is the phase modulation of the pump wave that leads to both idler spectral broadening and small signal gain distortion [6]–[8].

The influence of pump incoherence in nonlinear optics has been extensively studied in the framework of modulation instability of incoherent wave packets and has lead to the concept of "white-light" solitons [9], [10]. It was found that, under certain conditions, the pump incoherence may even enhance, rather than suppress the modulation instability (or parametric) gain [11]. In addition, the modulation frequency can be substantially increased with respect to the corresponding value of the coherent case due to field amplitude fluctuations [12].

From a fundamental point of view, these vector nonlinear phenomena are closely linked to parametric amplification, since it also leads to soliton-like pulse train generation with a corresponding repetition rate equal to the pump-signal frequency detuning. More precisely, parametric amplification can be thought as a small signal-induced modulation instability process.

The purpose of this work is to better understand and quantify the detrimental role of pump incoherence on the performances of parametric amplifiers. To this end, we revisit the principle of operation of fibre optical parametric amplifiers by taking into account the pump wave characteristics, ranging from the monochromatic coherent case to the incoherent one. Particular emphasis will be given on the partially coherent pump using the phase modulation and the phase diffusion model [13]–[15]. Unlike for modulation instability, it is shown that for a certain degree of incoherence the parametric gain is always reduced, in particular near the exact phase-matching condition. Fig. 1 illustrates this situation that shows the parametric gain bands obtained from numerically solving the nonlinear Schrödinger equation for an increasing pump linewidth (or decreasing coherence time). In addition, pseudo-random bit sequence (PRBS) phase modulation of the pump has an impact on the parametric gain at high modulation frequency. As an example, Fig. 2 shows the gain penalty when increasing the PRBS modulation frequency.

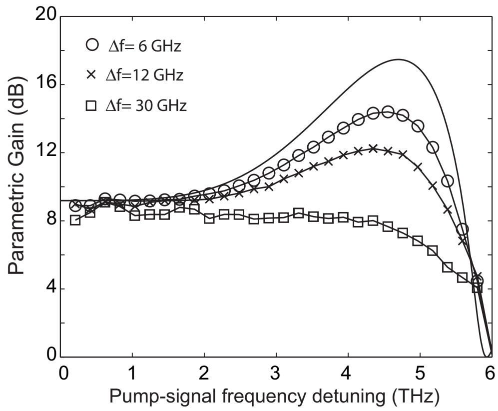

Fig. 1. Parametric gain spectra for a monochromatic pump (solid line), and partially coherent pumps with increasing pump linewidth (or decreasing coherence time). Parameters are pump power P=500 mW, fibre parameters are β_2 = 0, $\beta_3 = 1.2 \times 10^{-40} s^3 m^{-1}$, $\beta_4 = -2.85 \times 10^{-55} s^4 m^{-1}$, L=300 m and $\gamma = 18 W^{-1} km^{-1}$.

The reduction of the parametric gain under partially-coherent pumping can be understood by considering the pure monochromatic pump. In such a case, the phase relationship between the pump, the signal, and the idler waves is fulfilled all along the amplifier span with a corresponding maximum exponential gain until the pump depletion regime. For a partially-coherent pump field, however, phase-matching is satisfied over a limited distance corresponding to the pump coherence time. The parametric amplifier thus becomes phase sensitive and, consequently, the parametric gain decreases. Such a situation is clearly illustrated in Fig. 3 that shows the parametric gain in function of the amplifier length for the pure monochromatic pump, the PRBS phase-modulated pump, as well as the partially-coherent one.

Our results highlight the crucial issue of pump wave coherence on the gain of parametric amplifiers. While one pump

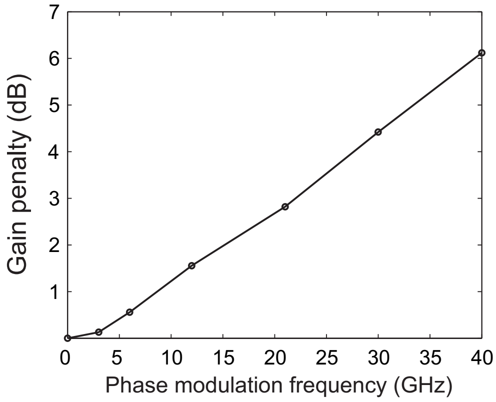

Fig. 2. Parametric gain penalty in function of the phase modulation frequency of a monochromatic pump. Parameters are pump power P=800 mW, fibre parameters are β_2 = 0, $\beta_3 = 1.2\times10^{-40}s^3m^{-1}$, $\beta_4 = -2.85\times10^{-55}s^4m^{-1}$, L=2 km and $\gamma = 2W^{-1}km^{-1}$.

FOPA allows for the achievement of efficient signal-processing techniques [3]–[5], counter-phase modulation of two low-noise pump in two-pump FOPA seems to be the best solution since it suppresses both idler spectral broadening and signal gain distortion [16], [17]. This pumping scheme requires however costly high-speed phase modulation architectures and high-power Erbium-doped fibre amplifier (EDFA). Moreover, the noise figure of parametric amplifiers is usually degraded by the remaining amplified spontaneous emission (ASE) from the EDFA [18], [19]. The use of the recently-developed low-noise narrow-linewidth high-power laser as a parametric pump could be an alternative cost-effective pumping scheme [20]. Finally, it is now possible to think about alternative solutions for passive suppression of Brillouin scattering that requires no pump linewidth broadening, by using for instance the phononic bandgap properties of microstructured fibres [21], [22].

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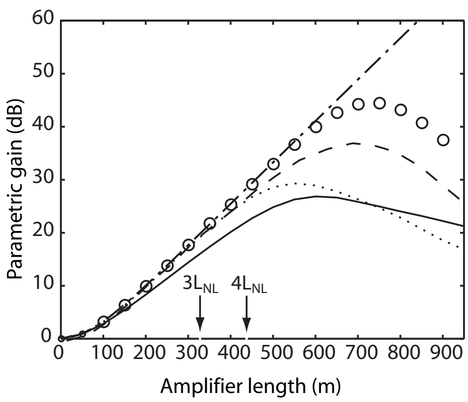

Fig. 3. Parametric gain in function of the amplifier length for a monochromatic pump (cercles), a PRBS phase-modulated pump (dashed), a partially-coherent pump with Δf = 6 GHz linewidth and with $\beta_3 = 1.2\times10^{-40}s^3m^{-1}$ (solid line) and $\beta_3 = 0s^3m^{-1}$ (dotted line). The dashed dotted line shows for comparison the usual analytical gain expression.

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